GEOCHRONOLOGIC METHODS FOR KARST

By

Douglas J. Frost

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Sidney E. White

Sidney E. White
Advisor

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Abstract

Karst topography is related to specialized climatic and lithographic criteria. Through an understanding of these basic processes an interpretative analysis of geochronologic dating can develop into an informative sequence.

Chemical formula of karst, which I have first outlined, is essential to the question of location of such topography. The next logical step is defining those forms of karst which are found in temperate climatic areas. These can be applied to give relative dates of development. Special attention was applied to subterranean karst since these features tend to prevail longer than contemporary surface structures. Indirect methods for relative dates were also included to show they can be used in conjunction with the other principles. Finally, two practical examples, using these techniques, are shown. The central Kentucky and southern Indiana karst regions were studied in order to place relative dates on the formation of the cave systems.

This accumulation of the various methods based upon the knowledge of karst formation will show the state of karst studies in today's text. By using these systems, a resolution of the question of ancient karst time tables can be pursued.

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Process of Karst

Before a serious undertaking of any science can be performed, constants of definitions and methods must be established. The understanding of karst, like other geologic processes, has been built upon by countless workers, and it is from these the following has evolved.

The term karst is derived from the German form of the Slav word krs or kras, meaning rock. Originally, it denoted a regional area of massive limestone to the north and south of the part of Rjeka in Yugoslavia. This area was characterized by great numbers of sinkholes, karren, and underground streams. Today the term is used more widely to classify a type of terrain with distinctive and unique landforms caused by the solution of rock.

With the morphologic investigation of karst in heated research, criteria for karst was generally established by 1930. Grund, Katzer, and others were responsible for the research to this point. They maintained the following: (1) The relationships between soluble and other rocks shows definite geomorphic landforms. (2) The relationship between soluble and insoluble rocks may modify the circulation of water in joints, fissures, and fractures and influence the development of karst features. (3) The lithology of karst relief is decisive; however, formation of karst is dependent upon exposure of coverage by alluvium and other sediment deposits. (4) Water was determined to be the medium for the solutional process. A method of defining climatic-ecologic influences was discussed in several papers; however, none agreed upon this classification. (5) The circulation of water through fractures was determined by Lehmann in 1932, but not convincingly demonstrated until Corbel in 1957 gave proof of movement of water several thousands of meters below sea level. Thus, the standard for evaluation of karst was evolved, and it is from these that various systems of nomenclature are borrowed (Herak, 1972).

A workable translation of karst process could simply be stated as the solution of limestone rock by acid through the medium of water, with or without subsequent deposition of by-products. Thus karren (karst features) found in limestone is true karst. Karren found in granite or sandstone is considered pseudo-karst phenomena. Basis of karst is therefore dependent on rock type (Paloc, 1966).

Chemistry of Karst

The climatic-ecological variables affect the dynamic process of karst in two ways: first, it determines the rate of reaction, and secondly it gives variance to the amount of material available for reaction. The process remains the same chemically whether it is alpine or tropical karst in question.

The formula of solution can best be shown by using the Debye-Hickel method (Daniels, 1955).

V = activities coefficient

K = equilibrium constant

$$\frac{(H_2CO_3)}{CO_2} = \frac{V_c}{V_o} K = 10^{-1.47} \qquad (1)$$

$$\frac{(H^+)(HCO_3^-)}{H_2CO_3} = \frac{V_o}{V_H V_1} K_1 = 10^{-6.30} \qquad (2)$$

$$\frac{(H^+)(CO_3^{2-})}{HCO_3^-} = \frac{V_1}{V_H V_2} K_2 = 10^{-10.30} \qquad (3)$$

$$(Ca^{2+})(CO_3^{2-}) = \frac{1}{V_{Ca} V_2} K_C = 10^{-8.28} \qquad (4)$$

$$(H^+)(OH^-) = \frac{1}{V_H V_{OH}} K_w = 10^{-14} \qquad (5)$$

As we see, the log of the number is actually in pH readings. This can tell us some important information in that any water not in dynamic equilibrium under these conditions may dissolve limestone. More often in the study of karst water, we look for the state of saturation with respect to calcite. This can be done by either comparing the product of the measured Ca^{2+} concentration and carbon dioxide partial pressure with the saturation product of calcium carbonate at the desired temperature or by comparing measured pH and Ca^{2+} concentration with equilibrium curves of Trombe (1952).

The question of the formation of the carbonic acid has seen much debate within recent years. Most feel that the carbon dioxide is developed in soil conditions. The normal atmospheric pressure of carbon dioxide is 3.0×10^{-4} ATM. Rain water, in equilibrium with atmospheric carbon dioxide, should contain 1.37×10^{-5} moles per liter of CO_2.

It was recognized that the soil contained many more times the carbon dioxide content than the atmosphere. Gerstenhaur used a technique applied to karst studies by Miotke (1968) of the measurement of CO_2 in the atmosphere. He found in a study of the soil that seasonal fluctuation from .04% to 3.7% of carbon dioxide has corresponding variations in the air at grass level. He summarized that there was a strong correlative effect between soil-air carbon dioxide content.

One important point in the discussion remains to be seen. The solution of bedrock is dependent upon the absence of the vapor phase of carbon dioxide during downward trend. If it becomes an open system, then the carbon dioxide is regained by the air with subsequent deposition of calcium carbonate.

Karst Forms

The formation of karst forms is a function of maturity of the terrain on which it develops. An unspoken code of definition exists among the researchers in this field of study. The various landforms are more easily understood if separated into those forms above ground and those below the surface. While it is true that those forms above the ground tend to be larger and better defined, those features found in the subterrain are more often preserved as characteristic indications of paleohydrologic factors.

We shall begin our review with those surface karst forms found in the middle latitudes (Gvozde, 1961).

Karren (lapies) are solutional features characteristic of the barren calcareous surfaces, considered by many to be isolated cyclic processes which do not pass into larger forms. It is indicative of pure, hard limestone types (Cviji'c, 1924). Jamas, deep open pits, are solution features developed from fractures and fissures in limestone. They connect surface with underground cavities. Little is known of their development; they are, however, similar to ponors, which are swallow holes. Both are rarely accessible features, difficult to study firsthand.

Kamenice are shallow dish-like impressions on consolidated calcarous blocks. These are excellent examples of marginal corrosion due to a lack of vertical jointing.

Dolines are considered the fundamental features of classic karst topography. They are the sinkholes which develop with maturity of such landforms. Usually found in massive phases of limestone, the factors controlling development are (1) geologic structure of limestone, (2) relief of the land (as a function of water runoff), (3) variations of the water level within the limestone, (4) climatic factors, (5) vegetative cover (determines solution process and can modify water discharge patterns).

Uvalas are next in the cyclic sequence of doline formation. This type is formed when dolines enlarge until a narrow bridge of land separates them. The bridges tend to coalesce to give it a distinctive characteristic.

Polje is considered a later form of karstic cyclic development. It refers to the impervious beds and deposits overlying many karst limestones and surface fluvial modelling. In one respect it can be a depositional feature in that fragmented rocks are lithified by calcium carbonate deposited into breccias or conglomerates.

Rillen karren and Rinner karren are specific forms of karren and need greater attention. These may vary from a few centimeters to about 20 meters (Bögli, 1960). Solution of limestone beneath vegetation cover produces types of microlandforms different from those formed from the action of intensive rain showers upon bard limestone surfaces.

As stated previously, certain karst forms may be given as a function of cover. Quinlan (1972) had detailed karstic types by using physical parameters of cover, lithology, climate, geologic setting, physiography, hydrology, modification of karst before and after dominant process, and types of major landforms. We are interested now primarily with preserved surface paleokarst forms. In order to preserve these forms the karst must be buried due to the fact that karst is a continuing process and would soon be diminished by more recent solution.

The four basic types of covered karst (Quinlan, 1972) are (1) subsoil karst, covered with residual soil (the Mammoth Cave area in the Mississippian Plateau of central Kentucky is an example), (2) mantled karst, covered by a relatively thin veneer of postkarst rock or sediment (an example of this type is the Mitchell Plain of Indiana), (3) buried karst, covered by a relatively thick cover of postkarst rock or sediment (not part of a comtemporary landscape as are the first two), (4) interstratal karst, covered by prekarst rock, formed by solution of limestone in the subsurface. The problem is, therefore, twofold: identification of relic karst as opposed to recent and determining the relationship of the covering material to the landform.

This can be solved by using those forms produced beneath the original surface. Features found within this realm can be categorized into three groups: negative, positive, and subsurface.

Negative karstic relief is basically that which is dissolved from the limestone. Included in this group are sinkholes formed primarily by acidic water perculating down vertical fractures above the ground water table. They are considerably more complex than was first realized in that they bear a direct relationship to the impermeable caprock. The prerequisites for development include: (1) thick limestone sequence, (2) method of penetration of caprock, (3) capture of surface flow. Pits are entirely or partially opened structures of this type, while sinkholes are obstructed versions of these cylindrical forms. Domes refer to the concave portions of pits at the top or entrance of water flow from within the cave (Quinlan, 1972).

Minor forms are negative stalactites and negative stalagmites. These form when water flowing through the fractures and fissures is still acidic in content and makes a perfect inverse pattern of the positive variety.

Fluting marks are vertical solutional ridges on the walls of pits. They are most constant where the limestone is homogeneous.

Scallops are found where water is actively moving across a limestone cave wall. They vary in size from a centimeter up to a meter in width. Often found in cave passages, they denote an eroding stream condition. Scallops also form on pit walls. These are good indicators, along with flute marks, of a change in flow rates of water entering a pit.

Fluting marks with scallops imposed, therefore, mean an increase of water over time into a given pit.

The positive forms of karst are formed by the depositional processes of the karstic cycle. The minerals most commonly found include calcite, aragonite, gypsum, celestite, and some clay minerals (impure iron oxides). The several ways chemically these substances are deposited include escape of the carbon dioxide of the water into the atmosphere (if the carbon dioxide pressure is less) with subsequent deposits of dissolved material. The mechanisms include evaporation and/or activation by splash or stream wall contact.

The principal forms for our study include the stalactite. By evaporation of water, these are grown by addition of material in a precise concentric ring as they grow outward and downward.

Stalagmites develop on the floor of caverns by the splash effect, thus releasing carbon dioxide and material. They show no given pattern of growth except as a function of growth water (with constituents) available.

Spillovers of water in caves tend to produce gours or dams. The carbon dioxide is released and the evaporation is increased with agitation. Spillover points are projected radially outward and upward forming the circular arcs of dams, convex downstream. If distributed over an increasing area and then adjoining dams coalesce, they form terraces of rimstone dams (Lange, 1968).

Flowstone is a structureless depositional feature that tends to coat cave walls with varying thicknesses. It can be produced by either dripping or flowing water along a cave wall.

Cave coral is an encrusting, mammilary or bulbous type relief which develops under submerged conditions. This can develop in standing pools although flowing streams are the more common method of deposition.

Up to this point we have described various formations beneath the surface. Many more types do develop and just as surface features, the criteria for their growth is exacting. Availability of material, temperature requirements, humidity, among others, geneally make these unsuitable for geochronologic interpretation until more research is performed. The relationship of bedding planes and joints control the location of these features in the cave proximity.

The third group of karstic features is the subsurface type. This includes breccia pipes formed by stoping over voids. Although not common, these can be well preserved and extend 3000 feet above gypsum beds (Landes, 1945).

Beds of solutional breccia formed in response to the widespread leaching of relative soluble rocks is still another feature. Principally, these are residual deposits, possibly altered by weathering or fillings of various types of solution-produced cavities (Quinlan, 1972).

The major type of subsurface karst is caves. In reality, this includes all the processes and forms described to this point. We can thus add that this includes all the various fillings of travertine, collapsed rock from ceiling and wall, and both fluvial and aeolian sediment. To make serious interpretative analyses of their formational sequence we must realize and understand the physical entities involved.

Karst formations can be separated by area on basis of mountain-platform structures. We are concerned with the horizontal areas or platform terrain. It is notable, however, that caves in folded limestone regions have received special attention due to the possibility of evaluating the factor of solubility in the different limestone beds (this stems from the fact that caves tend to form along the trace of a fold in such formations) (Moore, 1960). This has led some workers to classify caves into a given "cave physiographic province," by such attributes as the same formation or the same general geologic history. Horizontal or flat lying rocks are those dipping less than five degrees.

Next a study of the relationship of the joints and fractures should be reviewed. We need to understand the physical development of cave genesis to see such a working order. Vadose caves, such as defined by Davis, Rhoades, and others, include the structural concept of eroding vertically oriented seepage generally above the ground water level. Pits and sinkholes are examples of vadose structures. Water table caves are those that form by relatively fast flowing which is being discharged along the top of a quasi-static reservoir. It is almost impossible to demonstrate the quasi-static realm; thus the matter becomes that of a comparative scale. Swinnerton allowed 200 feet along a vertical zone of the water table for his model of development. This type poses considerable conceptual problems of scale. Phreatic caves are those formed below the level set for water-table type caverns (Ford, 1971).

Several corollaries can be set forth from the above. Water will strive to flow along the gradient, or path, of maximum potential difference. Those systems obtaining a nearly vertical flow (or drop) will consequently have a higher rate of solution. Ford found the type of cave developed was governed by the frequency of fissures significantly penetrated by ground water and the geometric proportionality (bedding ratio: joint ratio) of the fissure network. Thus, we see the indirect consequences of solutional effects of ground water. Horizontal areas tend to make horizontal passages due to the lay of ground water regimens.

Shapes themselves of the caves are controlled by rates of reaction. Generally uniform solution rates are constant around the walls of a structure (Lange, 1968). Nonuniform solution, then, reflects differences of temperature and pressures. Lange (1968) has calculated constant and exponential gradients reflecting these changes. He has found the tendency for rounded objects to have sharpened corners under solution where sharpened inside corners tend to round inversely.

Geochronologic Methods for Karst

For any age determination of a geologic feature some knowledge of the development must be made beforehand. The following can be considered guides to the recognition of paleo surfaces. The most obvious is the physical and paleontological characteristics of unconformities. Structures previously mentioned serve as guides and indexes of such relief. In association with the unconformities there are three types of probable boundary changes: (1) silicification described by Leith (1925) in which weathered carbonate had been replaced by fine, lacey silica. (2) Dedolomitization occurrences might also be useful (Filkman, 1969), but this may prove to be ambiguous because it also occurs in the vicinity of solution breccia horizons and it is therefore commonly a result of interstratal karstification. (3) Due to the differential breaking of calcite and secondary enrichment in phosphates, many inconformity horizons are characterized by slightly phosphatic surfaces (Cook, 1970).

The occurrence of length-slow chalcedony in solutional breccias may be quite useful. This form occurs when it replaces an anhydrite or gypsum or when it replaced carbonate minerals in an evaporite environment.

If the karst is more recent (which is to say if it is subsoil or mantled karst), then we can use depositional features such as those found in caves to determine a span of development for them. It must be understood, however, that these forms represent the second part of growth for karst. Few are made until the cave has been opened to outside atmospheric conditions.

Carbon 14 dating can be used by the following reasoning. The CO_2 used to dissolve the $CaCO_3$ comes from decaying organic material, thus it will have normal C^{14} concentrations. HCO_3 ions formed from the CO_2 will completely mix with the $CaCO_3$. On redeposition of the $CaCO_3$ the C^{14} will at least be half of that of a tree on the outside. Accuracy of $\pm$ 2000 years back to 30,000 years is possible (Broecker, Olson, 1959).

It is possible to use isotopic oxygen ratios as climatic indicators. Temperature dependent fluctuations in the O^{18}/O^{16} composition of calcite deposited in speleothems has been the principal method brought forward. It is determined by two factors, the isotopic concentration of the water going over the structure and the temperature at which the calcite is deposited. In conjunction with C^{14} dating, it can be related to other geologic events (Hendy, Wilson, 1968).

In some caves Th^{230}/U^{234} ratios can be determined. This is, however, dependent upon depositional minerals in the formations. This method could give dates as much as 350,000 years before the present.

Those methods discussed previously are absolute time scale determinations. Many times financial resources or special depositional requirements make such methods inoperable. Relative ages can be conceived if time is taken to analyze variables that influence the structure of karst. Climatic data can prove useful to such interpretation. We have been making reference to middle latitudes of karst formation. All of these areas would receive the same amount of rainfall were it not for special topographic features and differences in altitudes. Prolonged periods of cold weather set up conditions for development of glaciers. The modern day examples could prove a valuable key to knowledge of past events. The Castle Guard area in the Columbia Icefield in the Canadian Rockies (Ford, 1967) are such an occurrence where close juxtaposition of karst, glacier, and periglacial erosional features can be observed. Karst features occur on surfaces recently abandoned by the ice. Outside the margins of neoglacial moraines, limestone surfaces are reduced to felsenmeer devoid of karst. Beyond 2300 meters from the glacier sinkholes are extensively developed. This area provides an excellent example of karst development at the periphery of temperate-climate glaciers (Ford, 1967).

The question of destruction of karst on barren rock is understandable. Yet what of those karst forms produced in the periglacial climate such an interstratal karst types where more ground water is available. It has been found that in the Knox dolomite in Kentucky, karst surfaces of 15 to 20 feet average depths with some going to 170 feet under a soil subsurface of 30 to 40 feet. Preservation of relic features contained therein would yield correlatable information. Previously existing barren rock, now covered, presents problems also. Trudgill (1968), working on karst in Ireland, has found published literature is contradictory, maintaining that the solution of limestone is greater under cover than those surfaces that are barren. He found a correlation between the pH of glacial till in drumlins and the percentage of carbonate within a till with the presence or absence of dissection beneath it. His results are preliminary and could reflect, chemically, reaction within the till itself rather than subsurface till relationships.

Probably the single feature of karst most researched is that of sinkhole development with its relationship to drainage patterns. Lithologic requirements are a massive limestone with a cap of resistant sandstone, shale, or chert. The solution of the limestone usually occurs on the edges of the escarpment, although domepits occur under the capping rocks. Mammoth Cave Plateau capped by the Dripping Springs escarpment represents such an occurrence, although the lower Pennyvile Plateau escarpment lacks any such pits. The relationship of its development seems to be one of maturity of the drainage system of the karst rivers. As old pits are destroyed by continued solution, new ones are created near the head waters of the river. This is due to the fact that most pits and sinkholes are found in valleys dissecting ridge masses. Quinlan and Pohl (1967) take the approach that vertical shafts actively promote slope retreat rather than are a consequence of it. The thought that pits and valley rivers bear a significant relationship is solidified by the difference in elevation of the lip of the sinkhole and that of the drainage river. Still much must be done before formulas can accurately determine time intervals.

Denudation rates applied to karst have been used in conjunction with carbon 14 dating where redeposition of dissolved material was found. This, however, leaves a wide margin of error in that precise areas of solution are at best conjectural. Jean Corbel has brought this phase of karst research into new light. He used the climatic formula of 4ET100 = dissolved CO_3 content, where E is equal to precipitation minus evaporation in decimeters and T is equal to the calcium carbonate in miligrams per liter. He used this formula in calculations of karst solution in the northern parts of Canada. Another worker in the field raises serious question with Corbel's formula. D. Ingle Smith, applying his results versus the formula, with the Canadian latitude 74°N, found solution about 2 mm per 1000 years. This was one sixth the value expected from Corbel of periglacial climate and continuous cover of permofrost. The equation was further modified by Williams in 1964 to give a more accurate field formula to work in karst. His additions are S = ETN/10D, where S is the limestone removed in meters per year, E is the mean annual water surplus in decimeters, T is the total hardness in ppm, D is the density of the rock, and N is the fraction of the basin occupied by the limestone.

Indirect relationships of denudation rates have also been applied. Measurements of pH, hardness, ratio of Mg and

Ca as they flow through karstic rock can give significant figures for rates of solution by applying ratios of these figures before and after they flow through a given terrain.

Methodology, when working with solutional and depositional characteristics, has spun off in search of relatable features. The black coating in some caves is caused by humic acid, the residue being humate. The insoluble akile-organic matter sometimes makes up 5-10% of a sample. In one recent study of a cave in Tennessee 71% of the residue was pollen and spore fragments of recent and Pleistocene age. Care should be taken in order that the top level of the cave which would contain the oldest fragments of such material be evaluated. On karst-formed ponds (such as filled-in sinkholes) pollen and spores do not fare as well. In one study of cores in the Mammoth Cave Plateau area several ponds were studied. In the south Dale pond 8 meters of clay was brought up. The first 7 meters contained recent spores denoting rapid deposition. Below 450 centimeters no spores or pollen were found, suggesting that either they were flushed out through fractures below or rapid decay plus a short interval of large accumulation of clay made conditions unfavorable (Wright, Sprass, and Watson, 1966). In recent years, some credibility to age determination of caves has been brought by vertebrate remains found in soil and sand deposits. In caves of the midwest two researchers, J. Kukla and V. Lozels, have found no vertebrate fossils older than Wisconsin age.

Another approach taken is the selective study of deposition of alluvium in caves. A pattern (due principally to hydrologic factors) has developed of such deposition--caves show no clay deposits that are not preceded by sand, gravel, and finally silt. This tends to be a function of water velocity as the level of water is eventually lowered or water diminishes in amount available, then the energy needed to carry large sizes of bedload decreases. I have often been able to dig through the silt and clay horizons to connect passages. The type of clay can lend important clues to formation of karstic terrain also. This can best be considered a paleoclimatic indicator. Most of the caves of Indiana and central Kentucky contain clay horizons which are primarily a red, reduced variety, reminiscent of the conditions today found in hot, humid climates. Correlation of clays or even entire sequences is possible when studying the alluvium within caves. Simultaneous events can then be understood more readily.

Other mineral species can also be found within the deposition of karst. Again, paleoclimatic indicators have been used to outline conditions in prehistoric times necessary for their formation. Pyrite and marcasite are found in some Ohio and Kentucky caves and are usually associated with reducing environments. Their breakdown by bacteria creates sulphuric acid which hastens the solutional methods typical of karst. Gypsum, which most people know as the "flowers" found in caverns such as Mammoth Cave, is probably the second most important element formed in karst next to calcium carbonate. It is formed by evaporation, with the fill of some arid lands in the southwestern United States comprised of 50% gypsum. Gypsum is found in nearly all the caves of Kentucky and Indiana. In Mammoth Cave the reaction which forms it is $4H^{+} + SO_4^{-2} + CaCO_3 \rightarrow CaSO_4 \cdot 2H_2O + CO_2$. It is characteristic of the dryer levels of the cave. Anhydrite, $CaSO_4$, is found in only the driest portions of the caves often in association with gypsum.

Celestite, $SrSO_4$, is the third most abundant mineral. The anthigenic celestite and primary gypsum are usually found together, the amount of celestite being limited by the element of strontium available in meteoric water. The sulphates are all indicative of an arid climate (Pohl and White, 1965).

Many other minerals occur within the confines of caves, such as malachite, magnesite, and hydrous sodium sulfate, but their relationship to previous karstic solutions and/or deposition is questionable. Until further study, their use as interpretative devices is questionable. Aragonite, polymorphic with calcite, could become a principal chronologic tool in determining absolute or relative ages of karst terrain. Some stalactites found in central Kentucky contain alternating bands of calcite and aragonite. Still stalactites of pure aragonite are known. Other occurrences include the clay banks along abandoned stream beds of caverns and in the gravel along active streams. Calcite is the stable form of the mineral under natural conditions. Aragonite will begin to convert to calcite upon heating to 400°C in dry air or at lower temperatures in contact with water. Recent studies by Siegel and Reams (1966) show interesting relationships. Calcium carbonate made by bubbling CO_2 through powdered calcite crystals, limestone, and coralline aragonite, when filtered and allowed to evaporate, at various temperatures yielded only calcite. Similar studies using dolomite and an artifically prepared aragonite-calcite mixture yielded calcite at lower temperatures and aragonite at higher temperatures. Researchers have found that the borderline cases of aragonite versus calcite formation are directly influenced by the amounts of iron, magnesium, and strontium within the solution. Rates of change, perhaps like the radioactive elements, could give valuable information on time of formation and original constituents of the area involved. Since aragonite is formed under a much narrower range of conditions than calcite and is much less widespread, its presence could be a key to its past (Mason and Berry, 1959).

Stalactites, themselves, have been used as an indicative source of minimum dating for karst topography. An object of known age, coated by calcium carbonate for x number of years, should upon examination of the thickness of coating give a relative age of deposition when applied to the largest formation in that particular cave system. Such formations are dependent upon the amount of ground water, lithology of that one area of occurrence, atmospheric carbon dioxide and fracture pattern of the locality. They are, however, independent of seasonal variations of temperature, rainfall, etc., and the entire cave system in general, i.e., where one stalactite grows fast, others 50 feet away may grow at a slower rate. Therefore, we see that such data in literature as "one inch every hundred years in growth" becomes meaningless.

Practical Applications of Geochronology

A system of definition is only valuable if it can be used. The following review and practical fieldwork will show the validity of such methods.

The Mammoth Cave - Flint Ridge network is perhaps the most extensively researched system in the world. A total length of 156 miles, estimations have shown the length to possibly go over 200 miles when further exploration is conducted. Dating the formation of the system becomes the task of immense magnitude due to its size.

In order to understand the development of the cave system, an interpretation of the central Kentucky karst area must be undertaken. This plain is part of a fairly continuous karst belt developed on Meramac and lowest Chester strata (Mississippian) which extends from southern Indiana through northern Alabama. The thickness of stratigraphic units vary with estimates of different workers. A regional, fairly uniform dip, to the northwest is the only feature of this strata continuous throughout the area.

Structural and stratigraphic controls have been shown to exist for the karst landforms by A. P. Howard (1968). La Valle (1965) indirectly related pit development to these stratigraphic influences.

Regional outcrops of these formations give a characteristic pattern of solution while the nature of the landforms are often not obvious. The outcrop pattern of the lower part of the St. Genevieve may be correlated with zones of "low" sink plains and to a lesser extent with high sink plains. The upper part of the St. Louis formation generally underlies broad, "high" sink plains. The lower strata of the St. Louis generally support surface drainage which in many instances disappears into the skin plains developed in the upper part of the St. Louis. The lowest part of the St. Louis limestone and the Warsaw-Salem and underlying formations are generally characterized by surface drainage with minor local sink zones. The major distinguishing formation is the Big Clifty Sandstone, part of the Chester series. This unit acts as an escarpment in the development of pits and solutional valleys in the Mammoth Cave area. This escarpment is called the Dripping Springs Escarpment in this region and separates the two major karst areas into the Pennyrile Plain to the south and southwest, and the Mammoth Cave Plateau to the north.

The Pennyrile Plain contains surface karst features such as dolines and polje which are only slightly developed. These occur mainly on the Warsaw, St. Louis, and St. Genevieve limestones and generally are smooth, lightly developed structures of less than 10 meters deep. Surface alluvium tends to disguise such features in this area from none karst area.

To the north lies the Mammoth Cave Plateau which contains much larger karst dolines. Averaging 30 meters in diameter, they extend to depths of 30-70 meters below the level of the rim. Large karst valleys were found on this plateau. The largest cave systems are found in this region which contains the upper part of the St. Genevieve limestone.

Most methods for dating karst would prove unacceptable for this large cave system. It contains at least 7 levels of identifiable passages including the ones now submerged. Alan D. Howard (1968) provided excellent statistics for this area in relating pit development to stratigraphic and structural controls--it is reasonable to assume domepits can only develop up to the highest level of a valley ridge, thus would prove useless in maturity rates for this karst terrain. Ph and calcium rates removal such as Corbel's formula would likewise prove unacceptable in that large widths of the passages (and the narrow vertical levels) provide information that solution has not been a constant factor. The most promising feature comes from correlation of the cave passage elevation to that Ohio River drainage basin during the late Tertiary and Pleistoene. Major cave levels have a distinct relationship to the flood plain development of the Green River which is the principal drainage system of the caverns. This can best be seen in several stages.

The first would be the Teays system, filled by Nebraskan till, diverted the head waters of the Teays into the Ohio

River Valley causing deep and rapid entrenchment during the Aftonian Interglacial Period.

The second stage would consist of Kanasan Glaciation partially alluviating the valleys and filling the caves.

The third stage would be the development of the Green River terraces at the same elevation of distinct cave level formation during the Yarmouth Interglacial Period.

The fourth stage, the Illinoian Glaciation, develops another level, with a gravel-fill locally in the cave and related terraces during the Sangamon Interglacial Period.

The final stage proves most complex. An uplift with subsequent downcutting was followed by a static period. The streams and weather change due to the Wisconsin Glaciation brought in the large amounts of reddish brown to red sandy silt formed during the Sangamon Interglacial Period.

The passages are found to be correlatable to terrace formation of the Green River, but some contradictory evidence has developed. Scallops in the southern portion of the cave network show drainage going to the south, not the northern path to the Ohio River system. Still, I feel this can be resolved by using other data found in the underground karst. Correlating clay deposits at different levels would show direction of flow prior to uplift. Also study of primitive flow patterns (perhaps causing the differences of karst development on the Pennyrile Plateau) would shed light on this subject.

Oxygen isotopic analyses of the deposition formations would confirm paleoclimatic conditions of the downcutting episodes. Absolute dating tends to give minimum periods of formation of the system. Dating of bat guano deposits by C^{14} methods gave a date of 38,000 years (Davies, 1972).

Large deposits of gypsum, anhydrite, and a type of reddish silt tends to substantiate the paleoclimatic conditions during the interglacial periods.

Much work remains to be done in pinpointing formational dates in this system, but it would be safe to say the solution began at the time of the Nebraskan period if our hypotheses are correct.

Taking another example from the field, we can use less rigorous methods for determining karstic geochronology. The area under study was the cave system of Garrison Chapel Valley, Monroe County, Indiana.

The stratigraphy of the region is similar to that of Kentucky. The crawford Upland in which this system is located is the Indiana equivalent of the Mammoth Cave Plateau. The St. Louis and St. Genevieve limestones are present. The Paoli Limestone here is similar to the Girken limestone in the Kentucky area. Dip of the bedrock is difficult to calculate since the individual units change in a short distance. A general figure is 25 feet per mile to the west (Gray, 1962).

Karst features on the surface include karren, limited to occasional outcrops of limestone at the peaks of hills and streambeds, and dolines of 10 to 20 meters depth at the higher elevations. Solutional valleys and pits tend to be buried by the glacial drift which usually accumulates in the valleys from 20 to 112 feet in thickness (Gray, 1962).

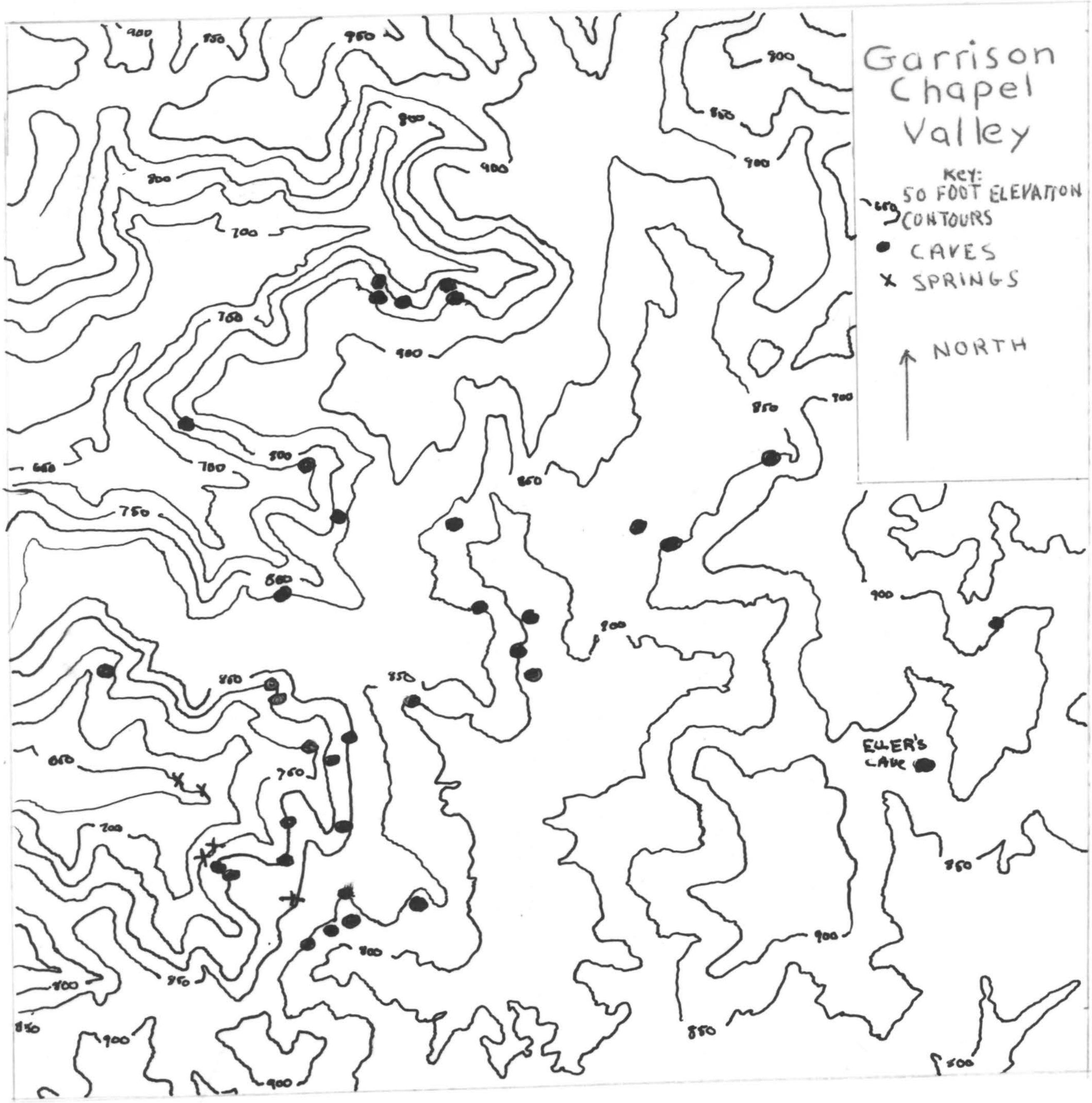
Again we must turn to the subsurface karst features to interpret a time scale to understand formational events. A good model for simple methods of chronologic determinations is one which has had both a constant rate of solution and also a stable drainage pattern. These exist only in theory, thus Garrison Chapel Valley is no exception. On a plain, just west of Bloomington, lies an area which is drained by great sinks opposite the heads of the streams in this region. A little further South Indian Creek begins on this plain and continues south with gentle grade compared with the previous streams.

The water entering the large sinks just mentioned is really the head waters of Indian Creek. The water, after entering these sinks, appears in the deeply incised heads of Richland Creek instead of continuing down Indian Creek, in other works, subterranean stream piracy by Richland Creek. This diversion of water was brought about by the location of the streams in question with respect to the rock structure. Indian Creek lay upon a table land of soluble rock with lower streams on either side of it. The headwaters of Richland Creek northeast of Stanford are at a level of 680 to 700 feet above sea level. They were cut by the top of the St. Louis Limestones which dip west from the Indian Creek plain into Richland Creek valley. A west branch of Indian Creek lay at an elevation of 800 feet but a half mile or more to the east. The divide between the two is formed of shales and sandstones (Beede, 1911).

The Garrison Chapel Valley system is a singular level complex of caves. This should, in comparison with the Kentucky example, show that conditions were different for development of the caves.

The map shows the locations of the known pits in the area. We must consider, though, that most are covered with glacial drift. It should be noted that none reach the highest elevations in this location which gives reason to assume that the maturity of this karst region is not as "old" as the fully developed system in the Mammoth Cave region (Powell, 1961).

This is not to say development of both systems formed independently. The type of terrigenous karst is similar to that formed in front of the Canadian Glacier example. The difference could therefore be the proximity of the glacier to the karst area and the variation of climate affecting the region (such as permafrost areas and amount of water available). By studying glacial boundaries in Indiana (Thornbury, 1937), it can be recognized that at least two of the glaciations extended over this system. Other supporting evidence for the relationship of these systems is the red soil in Indiana's Mitchell Plain, known in the area as "terra rossa." This is analogous to the red clay soil in the Mammoth - Flint Ridge System.


Garrison Chapel Valley
Key:
50 FOOT ELEVATION CONTOURS
CAVES
SPRINGS
NORTH
ELLER'S CAVE

The best methods are chosen using more absolute methodology. I used Williams' formula (1964) in doing a calculation of the rate of removal for this particular area. The formula is S = ETN/10D. The variables were previously discussed on Page 17.

The samples of water were collected at the points located on the map within the cave itself; a fifth sample was taken from a standing pool to provide a standard for the other samples. Corbel used calcium ppm in his calculations since other solubles should remain the same when strictly speaking of karst transformation rates. I, too, have taken this liberty in order to show my example more clearly.

E = The last 100-year average for rainfall was 44 inches. Evaporation is estimated in this section at 31 inches per year. This leaves 13 inches surplus or 3.3 decimeters.

T = The formula calls for total hardness; however, taking the preliminary hardness and final hardness (in this case hardness is equal to calcium in solution) then obtaining difference should give local solution of calcium. Ellers Cave calcium gave 58 ppm for an average of 56 ppm. The subsequent spring discharges gave 80 ppm and 64 ppm for an average of 72 ppm of calcium. Thus, 72 - 56 = 16 ppm.

N = Amount of basin occupied by the limestone. In this case only the argillaceous and chertbeds present give difficulties in a determative calculation. Both are local base levels for the cave at several points. By inspection of the system, no more than 25% of either of these are outcrops in our basin; thus N = 1.33

D = This is density, but if the limestone is not porous, then specific gravities can be used. On five samples obtained of the St. Louis Limestone of this cave an average value of 2.74 was obtained. Thus, D = 2.74.

The formula is therefore S = 3.3 x 16 x 1.33/10 x 2.74 and S = 2.56 m^3/ per year. By studying known systems in the area we find at least 25,000 feet of passages between Eller's cave entrance and the spring discharge point, with an average of 3 x 2.5 feet width and height.

The total volume removed is 7.5 x 25,000 = 187,500 ft^3. This is about 57,164 m^3.

Assuming constancy of conditions, this would assume to take 22,329 years.

Granted many variables can be entered into this formula such as true length, volume, etc., but the basic formation date of this system would still be well before the time of the Illinoian Glaciation.

Comparing the two examples given, climate and proximity to the recent glaciers could well account for their differences. This could well provide information that the glaciers had a direct effect upon karst development.

Summary

Geochronologic indicators for karst can be a useful tool for all phases of science. By defining conditions such as climate, topography, episodes of glaciation, and drainage, a possible clue for present surfaces exists.

Much research needs to be done; absolute dating should be precisely scaled to account for varying conditions. Relative methods can be worked out for many other constituents of both surface and cave karst. Considering the amount of oil found and other valuable resources within karst topography, it will be but a short time before this neglected field of geology is given due credit.

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